A review of forward proton tagging at 420m at the LHC, and relevant results from the Tevatron and HERA

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Abstract. We review the theoretical and experimental motivations behind recent proposals to add forward proton tagging detectors to the LHC experiments as a means to search for new physics. We also review the current diffractive programs at the Tevatron and HERA, focusing in particular on measurements which will have a direct impact on the case for forward detectors at the LHC.

INTRODUCTION

Diffractive physics has provided a rich supply of results from both HERA and the Tevatron. As an example, the measurement of the diffractive proton structure function from H1 [1] is, at the time of writing, the collaborations' second highest cited paper. It is fair to say, however, that diffraction has been used primarily as a tool for understanding and developing QCD, rather than as an area of study within which physics beyond the Standard Model might appear. There has been increasing interest in the past few years, however, in the possibility of using diffractive interactions as a search tool for new physics. In particular, it has been suggested that the so-called central exclusive production process might provide a particularly clean environment to search for, and identify the nature of, new particles at the LHC. By central exclusive, we refer to the process $pp \rightarrow p \oplus \phi \oplus p$, where $\oplus$ denotes the absence of hadronic activity ('gap') between the outgoing protons and the decay products of the central system ϕ. An example would be Standard Model Higgs Boson production, where the central system could consist of 2 b-quark jets, and *no other activity*. What is meant by *no other activity* is an important question, and we shall return to it later.

The process is attractive for two main reasons. Firstly, if the outgoing protons remain intact and scatter through small angles, then, to a very good approximation, the central system ϕ is predominantly produced in a spin 0, CP even state, therefore allowing a clean determination of the quantum numbers of any observed resonance. Secondly, as a result of these quantum number selection rules, coupled with the (in principle) excellent mass resolution on the central system achievable if suitable proton detectors are installed, signal to background ratios of greater than unity are predicted for Standard Model Higgs production [2], and significantly larger for the lightest Higgs boson in certain regions of the MSSM parameter space [3]. Simply stated, the reason for these large signal to background ratios is that exclusive b quark production, the primary background

in light Higgs searches, is heavily suppressed due to the quantum number selection rules. Another attractive feature is the ability to directly probe the CP structure of the Higgs sector by measuring azimuthal asymmetries in the tagged protons (a measurement previously proposed only at a future linear collider) [4].

Given the apparent benefits of the central exclusive process at the LHC, two key questions naturally arise. Firstly, do we understand diffractive processes well enough to use them as a search tool? This applies not only to the calculation of the production rates of new particles, but also to the potential backgrounds, most of which also come from diffractive (though not necessarily *exclusive*) processes? Secondly, is it possible to install leading proton detectors with the appropriate acceptance, and if so, be able to use such detectors at high luminosity and integrate them with the existing ATLAS and / or CMS trigger frameworks? In this paper we will review the current predictions for signal and background rates for a variety of physics scenarios in central exclusive production at LHC. We then survey the measurements currently being made at the Tevatron and HERA which will have a direct impact on the proposal to install forward proton taggers for the detection of the central exclusive process.

CENTRAL PRODUCTION AT THE TEVATRON AND LHC

There has been a healthy debate over the last few years regarding the many and different predictions for the production rates of Higgs bosons with two leading protons. Perhaps the clearest review of the competing models can be found in [5]. Here, the authors are careful to differentiate between *exclusive* production - the process described in the introduction above, and *central inelastic* production. Central exclusive production, shown schematically in figure 1 (a) for the example of the Higgs, refers strictly to the process in which the incoming protons emerge into the final state intact, having lost a small fraction of their energy, and the only other final state particles are the decay products of the Higgs Boson. Central inelastic production, shown in figure 1 (b), refers to every other process in which the outgoing protons remain intact - in the language of Regge-inspired models, there are pomeron remnants. Two important facts are worth noting. Firstly, central inelastic production is the only process so far unambiguously observed at Tevatron energies, and secondly, it is of no use in the search for new physics at the LHC. Having said this, however, understanding the central inelastic process is essential, because it will be the dominant source of background to the exclusive production process. We deal with this issue later. First, we review the signal and background predictions for the exclusive process at the LHC.

Predictions for exclusive production of Higgs Bosons at the LHC

It is the claim of Khoze et al. that the central exclusive process is perturbatively calculable, up to the un-integrated off-diagonal parton distributions of the proton (oduPDFs) [6], and the so-called gap survival factor which accounts for the probability that there are no interactions between the spectator partons in the protons, which would destroy the
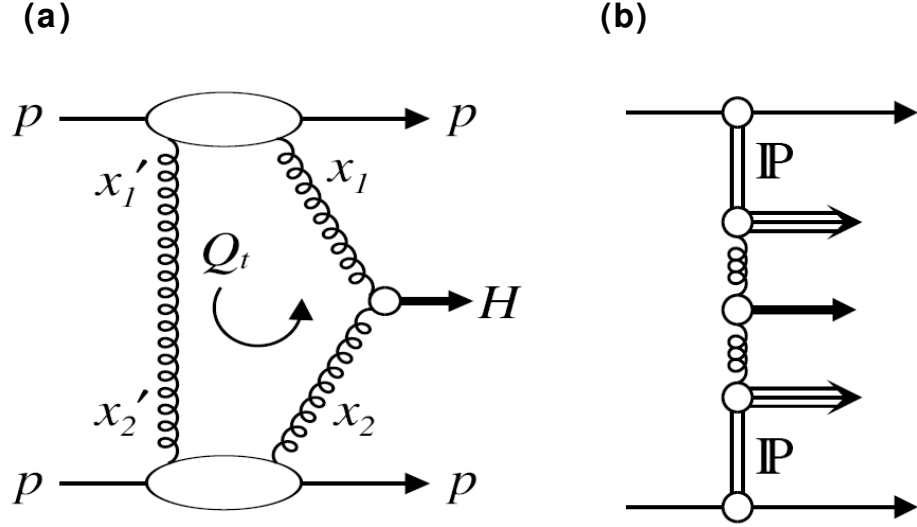
FIGURE 1. The exclusive production process (a) and central inclusive (or double pomeron) process (figures taken from [5])

protons and the gaps. Sudakov factors, which enter via the requirement that there be no radiation off the three exchanged gluons (see figure 1 (a)), ensure that (at least for scalar Higgs production) the dominant contribution to the integral over Q_t comes from the region in which Q_t is perturbatively large. This is to be contrasted with earlier approaches in which an infra-red cut-off was introduced 'by hand' and tuned to fit the total pp cross section [7, 8]. The earliest calculation of the process was carried out by Bialas and Landshoff [9], and has recently been updated by Boonekamp et al. [10, 11]. The early predictions for the exclusive Standard Model Higgs production cross section at 14 TeV were all extremely large (over 100 fb). If these predictions are correct, then detection of the Higgs using proton tagging will be very easy indeed [1] . The predictions of Khoze et al. are orders of magnitude lower. Fortunately, the calculations (approximately) factorise into a luminosity function, which contains the physics of the colour-singlet gluons, and a hard sub-process cross section. It is therefore possible to check the calculations by observing the exclusive production of other higher rate processes. We review the first experimental attempts to do so at the Tevatron below.

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[1] It is very likely that such large cross sections are ruled out by the CDF exclusive χ_C results discussed in the following section

According to Khoze et al. the cross section prediction for the production of a 120 GeV Standard Model Higgs boson at 14 TeV is 3 fb [6][2]. Apart from the estimates of gap survival probability (which are included in this calculation), one of the dominant uncertainties in the above calculation comes from the knowledge of the oduPDFs. Khoze et al. estimate the uncertainty to be a factor of 2, although a recent study by Lönnblad and Sjödahl suggests that the uncertainty may be rather larger (but below a factor of 10) [12]. We take this prediction as the benchmark result. For 30fb^{-1} of LHC luminosity, therefore, one would expect ~ 90 signal events. This is a small number, so the viability of detection depends crucially on the acceptance of the proton detectors, the efficiency of the trigger, and the magnitude of the background. De Roeck et al. have made a detailed study, including calculations of the $b\bar{b}$ backgrounds, the b-tagging efficiency and the acceptance and mass resolution of possible proton tagging detectors at LHC. b-tagging is necessary because the exclusive production of gluon jets is not suppressed and therefore has an extremely large rate which would totally swamp the Higgs signal. The bottom line is that, for a luminosity of 30 fb^{-1}, De Roeck et al. expect 11 signal events, with a signal to background ratio of order 1. Details can be found in [2], but we make a few remarks here. The very low $b\bar{b}$ backgrounds are a result, as mentioned in the introduction, of the spin selection rules which are a consequence of the colour-singlet configuration of the exchanged gluons (and the small transverse momenta of the outgoing protons). These selection rules are not exact: in fact the $b\bar{b}$ background is proportional to m_b^2/E_T^2, where E_T is the transverse energy of the b jets (which will be of order $m_H/2$). This is a small effect for a 120 GeV Higgs, but as we shall see, can be important for lighter Higgs bosons which might occur in certain regions of the MSSM parameter space. The selection rules can also be violated by higher order gluon emission. De Roeck et al. estimate the contributions from NLO and NNLO diagrams, and find them negligible. This result can (very crudely) be pictured as the statement that soft gluons do not flip quark helicities. There may be an issue here, however, as to what one means *experimentally* by a soft gluon. If, for example, a gluon emitted from an out-going b quark with a relative $p_T \sim 4$ GeV is sufficient to violate the selection rules, and yet cannot be resolved experimentally, then what is the resulting change in the background estimates? This issue has yet to be addressed in detail.

The mass acceptance and resolution of the forward proton detectors is also a crucial issue, which depends on many factors including the LHC beam optics, the distance of the detectors from the interaction point, the closeness of the active region of the detectors to the beams, and the accurate knowledge of the relative positions of the detectors to the beams. De Roeck et al. consider the case in which detectors are placed at 420m from the interaction point. This position is simply the distance from the interaction point, with standard LHC beam optics, that protons which lose transverse momentum $m_H/2 \sim 60$ GeV emerge at least 10σ from the beam. This large distance raises a serious issue. Without modification of the level 1 trigger systems of ATLAS and CMS, the light travel time from 420m detectors is very close to, and possibly larger than, the time required for a level 1 trigger decision. This means that a trigger strategy based on the central

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[2] The modified Bialas and Landshoff prediction, taking into account rapidity gap survival and other factors, leads to similar predictions [11]

detectors alone may be required, at least until the proton tagger information becomes available at level 2. For dijets of such low transverse momentum (~ 60 GeV), this is certainly a challenge. Both De Roeck et al. and Boonekamp et al. [11] consider some basic ideas based on the central system topology, but it is fair to say that much work still needs to be done in this area.

The resolution of the detectors is a crucial number. The signal to background $S/B \propto \Gamma(H \to g\bar{g})/\Delta M \propto G_F M_H^3/\Delta M$, where ΔM is the mass window within which the search is performed. This is easily seen: a search using this technique is simply a counting experiment within a mass window, and since the tagger resolution will always be greater than the Standard Model Higgs width, the worse the resolution the more continuum background will enter [3].

There is also the question of contamination from the central inelastic process, shown in figure 1 (b). As mentioned above, this is the only process so far observed at the Tevatron [13]. There are no selection rules suppressing $b\bar{b}$ production in this process, and it is therefore potentially a very large source of background. We consider this in the following section.

Finally, we briefly review two other scenarios in which forward proton tagging may be of significant interest at the LHC. Firstly, the 'intense coupling' regime of the MSSM. This is a region of MSSM parameter space in which the couplings of the Higgs to the electroweak gauge bosons are strongly suppressed, making discovery challenging at the LHC by conventional means. The rates for central exclusive production of the two scalar MSSM Higgs bosons can be enhanced by an order of magnitude in these models, however, leading to predicted signal to background ratios in excess of 20 for masses around 130 GeV[3]. This region of parameter space can also be problematic in conventional search channels because the masses of the three neutral Higgs Bosons are close to each other. Central production can help disentangle the Higgs bosons because, due to the spin/parity selection rules, production of the pseudo-scalar (A) Higgs is heavily suppressed. This means that the 'double tagged' sample will be almost pure scalar.

As a second example, Higgs sectors with explicit CP-violation [14] are also an area in which central production may prove extremely attractive. One such model, known as the CPX scenario [15], has been shown to lead to very light (less than 60 GeV) Higgs bosons which would have evaded detection at LEP, and may well evade detection at the Tevatron or LHC, again primarily due to the suppression of the coupling to the electroweak bosons of the lightest Higgs (which may be predominantly pseudo-scalar, since the mass eigenstates are not weak eigenstates in this case) [16]. The central production cross sections for the lightest CPX Higgs are relatively large at low masses [17], although the relaxing of the $b\bar{b}$ background suppression with mass (see above) probably means that the $b\bar{b}$ decay mode will not be a possible detection channel. The $\tau\tau$ mode may be possible, however, since the only background comes from QED production of τ pairs, which can be suppressed by demanding that the p_T of the tagged protons be greater than a few hundred MeV [4]. It was also noted in [4] that explicit CP violation in the Higgs

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[3] It is worth noting that in certain MSSM scenarios, the Higgs width can exceed the resolution of the tagging detectors, raising the possibility of a direct measurement of the width

sector will show itself directly as a (potentially sizeable) asymmetry in the azimuthal distribution of the tagged protons. This measurement is probably unique at the LHC, although little detailed phenomenological work has been done so far. First indications suggest that this may be a high-luminosity (300fb^{-1}) measurement, although models other than CPX have not been considered, and may possibly lead to higher signal to background ratios in the $b\bar{b}$ channel.

Predictions for the central inelastic process

Central inelastic production is usually referred to as 'double pomeron exchange', and can be modeled using a Regge - inspired picture involving a pomeron flux term describing the 'emission' of a pomeron from the proton, and a pomeron structure function. The parameters of the flux term and the structure function are extracted from diffractive deep inelastic scattering data by the H1 Collaboration at HERA [1] using a Regge factorisation ansatz[4]. This approach has been shown not only to describe a wide range of HERA data, but also the double diffractive dijet production data from the CDF Collaboration[13, 18], if a 'gap survival factor' is included to account for the fact that multi-parton interactions in proton-antiproton collisions will reduce the observed rate of double pomeron collisions. This factor can be extracted from data, by scaling the absolute predictions derived using the H1 diffractive structure functions [19], or calculated using phenomenological approaches of varying degrees of sophistication, but in general based on eikonal methods and total cross section measurements [20, 21, 22, 23, 24, 25]. It is the latter calculational approach that Khoze et al. use to estimate the gap survival probability in their central exclusive predictions. At least at Tevatron energies, the two approaches lead to similar results; the Regge-inspired predictions, normalised to the H1 diffractive DIS data, overshoot the measured double pomeron exchange data from CDF by a factor of approximately 10 [18, 19], and the predictions from the eikonal models are of a gap survival factor of approximately 0.1 [26, 27, 28]. This gives at least some confidence in the calculations of gap survival probability which are an important ingredient in predicting the central exclusive Higgs production rates at the LHC.

As mentioned above, understanding the central inelastic process is of prime importance. The cross section for the production of $b\bar{b}$ jets in central inelastic production is orders of magnitude larger than the exclusive process. The key to suppressing this background is to reject events in which there are pomeron remnants, either directly using the central detectors, or by requiring that the invariant mass of the dijet system is equal to the invariant mass of the central system as measured in the proton taggers. It is the latter solution that was used by De Roeck et al. [2]. This approach depends on defining which final state particles are inside the jets, and which are not, and is clearly extremely sensitive to the nature of the jet algorithm used. The CDF collaboration are currently using a similar method to search for evidence of the exclusive process. They define the observable R_{jj} as being the fraction of the mass of the central system contained within

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[4] H1 also require the addition of a reggeon term to fit the data at larger proton fractional momentum losses

the two highest E_T jet cones of radius $R_{cone} = 0.7$. Exclusive dijet production would be expected to appear in the high R_{jj} tail of this distribution. CDF measure the cross section for $R_{jj} > 0.8$, and find it to be consistent with the Khoze et al. predictions, although there are at present large systematic errors and theoretical uncertainties [30].

An alternative approach is to carry out a more sophisticated analysis on the central system itself - in essence using a subjet analysis to identify the presence of pomeron remnants. It is our opinion that such an approach will also be necessary to address the issue of moderate p_T gluon emission reducing the effectiveness of the selection rules, as mentioned above. This work is ongoing at the time of writing, and we intend to return to it in a future publication [31].

RECENT RESULTS FROM THE TEVATRON AND HERA

Clearly, the understanding of central dijet production is crucial for central Higgs production searches at the LHC. In terms of searching for evidence of exclusive production at the Tevatron, however, it is not ideal, given the difficulties in defining which particles are inside the jets. The CDF collaboration have therefore also begun a search for the exclusive production of lighter particles with the same quantum numbers as the Higgs. The lightest detectable particle (and therefore that with the highest cross section) is the χ_c, which is detected via its decay to $J/\psi\,\gamma$, and the subsequent leptonic decay of the J/ψ. Although this process appears rather simpler than the search for exclusive dijets, one still has to face the issue of defining *experimentally* what is meant by exclusive: it is feasible that soft radiation may go undetected in the calorimeter, and it is extremely difficult to put a figure on what is meant by 'soft'. For this reason, the CDF Collaboration present their results as an upper limit on the exclusive χ_c production cross section [30], assuming that all the χ_c candidates which appear to have no other activity in the calorimeter are indeed truly exclusive. The result is consistent with the estimates of Khoze et al. although due to the low mass of the χ_c, the theoretical calculations are subject to large uncertainties [32]. Exclusive diphoton production ($p\bar{p} \rightarrow p\gamma\gamma\bar{p}$ is also a promising channel which could be used as a 'standard candle' to check the calculations [33]. The central exclusive predictions are in the 10s of fb for photons of $E_T \sim 7$ GeV, whilst the central inelastic cross section is ~ 100fb [19]. This process should therefore provide a clean testing ground not only for the theory, but also for the experimental techniques used to separtate the exclusive and inelastic processes.

Another key area in which the Tevatron and HERA can make valuable contributions is in the testing of the models of gap survival probability. We have already considered the double diffractive dijet measurements from CDF, [13, 18], and concluded that in this case a consistent picture emerges between theory and experiment. Gap survival is also an issue in diffractive photoproduction at HERA, in which the resolved photon can behave as a hadronic object and therefore contain spectator partons which can interact with and destroy the diffracted proton just as at the Tevatron. The H1 and ZEUS Collaborations have measured the diffractive dijet cross section in photoproduction as a function of x_γ, the fractional longitudinal momentum of the photon which participates in the production of the two highest E_T jets [34, 35, 36]. Without taking account of gap

survival, the naive expectation would be that the predictions should match the data at high x_γ, where the photon couples directly into the jet production process, whereas at low x_γ, where spectator partons are present, the predictions should overshoot the data. A recent phenomenological study, which took account of NLO effects, found that at low x_γ a suppression factor $S = 0.34$ was required to fit the data [37] [5]. This is in agreement with the calculations of [38].

To summarise, all the diffractive results from HERA and the Tevatron are at the time of writing consistent with the expectations from the theory of exclusive and inclusive production and gap survival probability. However, this is not to say that the data as it now stands should give us blind confidence in the predictions at the LHC. The exclusive process has certainly not been unambiguously observed, although with increased luminosity at the Tevatron Run II it certainly should be seen within the next few years if the calculations are correct.

SUMMARY

The installation of proton tagging detectors in the 420m region around ATLAS and / or CMS would certainly add unique capabilities to the existing LHC experimental programme. If the current calculations of central exclusive production rates survive the experimental tests at the Tevatron, then there is a very real chance that new particle production could be observed in this channel. For the Standard Model Higgs, this would amount to a direct determination of its quantum numbers, with an integrated luminosity of order 30 fb^{-1}. For certain MSSM scenarios, the tagged proton channel may be the discovery channel. At higher luminosities, proton tagging may provide direct evidence of CP violation within the Higgs sector. There is also a potentially rich, more exotic physics menu which we have not discussed, including gluino and squark production, gluinoballs, and indeed any object which has 0^{++} or 2^{++} quantum numbers and couples strongly to gluons [6]. Given the relatively low cost of such a project, and the potentially unique access to new physics, we believe the installation of 420m proton detectors at LHC should be given careful consideration.

ACKNOWLEDGMENTS

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[5] This result has recently been confirmed by the H1 and ZEUS collaborations, with slightly varying figures for the suppression factor [35, 36]

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